# Effect of plant traits and substrate moisture on the thermal performance of different plant species in vertical greenery systems

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## Highlights

- Vertical greenery systems (VGSs) significantly reduced canopy air temperature.
- Leaf area index and coverage regulated canopy temperature reduction on sunny days.
- Substrate moisture strongly affected substrate temperature reduction.

## Abstract

This study evaluated the effects of plant traits and substrate moisture on the thermal performance of four herbs and four shrubs, which are the most commonly used species in vertical greenery systems (VGSs), in humid subtropical Hong Kong over a one-year period. The canopy temperature reduction on sunny days was significantly correlated with canopy coverage and leaf area index (LAI), but not with daily evapotranspiration (ET). This indicated that the shading effect of VGSs, which is related to canopy coverage and LAI, was more prominent than ET cooling. The lack of significant correlation between substrate moisture, ET and canopy temperature indicated that substrate moisture and ET did not significantly enhance the canopy cooling of VGSs. Substrate moisture notably cooled the substrate on sunny days, and warmed the substrate on rainy days, which significantly affected substrate thermal behavior, but had less effect on canopy air temperature. The use of VGSs with eight common plant species on building envelopes reduced steady-state heat conduction by 18.7–39.8%, with *Ficus elastica* (rubber fig) causing the greatest canopy cooling.

Keywords: vertical greenery systems, plant characteristic, substrate moisture, thermal performance, cooling effect

## 1 Introduction

The modification of the thermal conductivity, heat capacity and land surface emissivity of urban areas due to land use/land cover change (LUCC) has led to the aggravation of the urban heat island (UHI) effect. To address this problem in the built environment, the use of vertical greenery systems (VGSs) has become increasingly popular [1,2]. VGSs can be categorized according to the position of the growing media into two major types: green façades (in which the growing media remain on the ground) and living walls (in which the growing media stand vertically in front of vertical building surfaces) [3]. VGSs not only improve the aesthetics and biodiversity of urban environments, but also enhance the energy efficiency and sustainability of buildings, especially via energy saving through heat insulation and UHI mitigation [1-4]. The vertical greening of building envelopes can reduce canopy, wall and ambient temperatures through shading effects [5-8], the insulating capacity of plants and substrates [6,9,10] and evapotranspiration [7,11].

Plant species vary in their thermal behaviors due to a range of intrinsic characteristics, such as canopy cover, foliar thickness, leaf number, leaf angle and leaf area index (LAI). Previous studies have suggested that the LAI of vegetation is associated with its shading effect [12-14] and the insulating properties of vertical greenery [6,15]. Susorova et al. [16] suggested that VGSs with high LAI and leaves parallel to the wall (which generates high attenuation coefficients) performed best at decreasing the wall surface temperature and heat flux, due to the favorable range of leaf angles. Koyama et al. [17] found that among various plant-based parameters in VGSs, the percentage cover of vegetation had the most profound effect on wall surface temperature reduction. Charoenkit and Yiemwattana [7] suggested that VGSs with plant species with smaller leaf sizes had better cooling effects. Certainly, vigorously growing plants can achieve full cover and provide substantial ecological benefits [18], making them the key to successful establishment of VGSs. Hence, it is essential to select plants with high LAI for VGSs, as these will give high coverage under prolonged elevated outdoor temperatures and possible water stress, thereby providing multiple ecological benefits for building envelopes and microclimates, such as ambient air temperature reduction.

The relationship between the thermal behavior of VGSs and plant type implies that substrate–moisture interactions may possibly influence evapotranspiration. For green roofs, substrate moisture content has been found to consistently increase thermal conductivity across a range of substrates and heat capacities [19], affecting downward heat transmission and the fluctuation of substrate temperature. Furthermore, substrate moisture regulates the availability of water for substrate transpiration and vegetative evaporation [20], which contributes to the latent cooling of building environments and accounts for a considerable proportion of the cooling effect. However, few studies have explored the effects of soil in VGSs. Although previous studies suggested that plant characteristics affect the thermal performance of VGSs, there is a lack of knowledge on the substrate thermal behavior and water balance of VGSs. It is also unclear which plant species that are widely used in VGSs have the most favorable plant characteristics and thermal performance. The role of substrate moisture in the thermal performance of VGSs has yet to be examined.

This study was performed to assess the growth and traits of the most commonly planted herbs and shrubs in VGSs, and to assess their thermal performance under typical weather conditions for one year in humid subtropical Hong Kong. The correlation between thermal properties and plant traits was evaluated. In addition, the substrate temperature regime and water balance of the VGSs were investigated. These resulting findings on canopy air temperature reduction and substrate thermal performance in VGSs will deepen our understanding of the role of plant traits and substrate moisture in thermal performance of VGSs, and inform plant selection in the design of VGSs to maximize their environmental benefits.

## 2 Materials and methods

### 2.1 Study area

The experimental site was located on the main campus of The Chinese University of Hong Kong, located in the New Territories, Hong Kong (N 22° 25′ 10″, E 114° 12′ 24″). The annual precipitation is 2,300 mm and the relative humidity is 78%. The annual wind speed is 11.0 km/h, mainly from the east. According to the climate data provided by the Hong Kong Observatory, the mean temperature between May and October in 2014 was 26.2–29.8°C [21]. In the hottest months (June to September) the monthly means of daily maximum air temperature were 31.5–32.6°C [21].

## 2.2 Experimental design

Nine VGS treatments were studied, comprising eight VGSs with different plant species and one VGS with no plants. All nine VGSs had west-facing modular planters (33 cm × 50 cm), within each of which were nine pots (10 cm diameter). The treatments were arranged in randomized blocks in the modular planter, and there were three replicates for each treatment (Figure 1). The eight plant species were chosen because of their suitability to subtropical climates in vertical greening, price attractiveness and market availability, and were among the species most commonly used for VGSs in Hong Kong (Table 1). The substrate was a mixture of light growth media, comprising coco fiber, peat moss, potting soil, perlite and vermiculite. This substrate had good drainage and aeration properties, with a water holding capacity of 18% (v/v) and a saturated moisture content of 0.422 $m^3$ $m^{-3}$. The pH was between 5.6 and 6.3, and the bulk density was approximately 1.23 g $cm^{-3}$. The VGSs were watered thoroughly in the morning and evening by a battery-controlled irrigation system, which was adjusted seasonally. The experiment was conducted for 12 months from September to August.

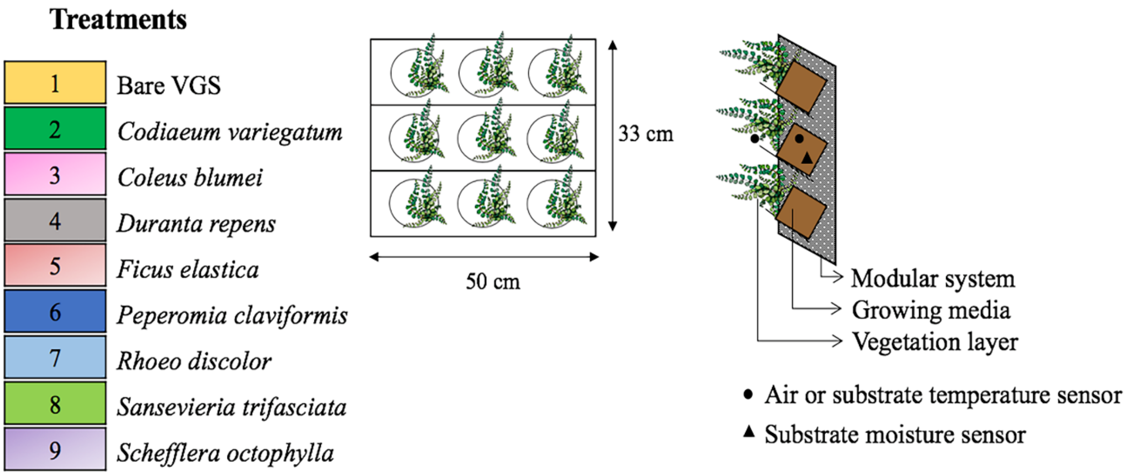


Figure 1. Experimental design of nine VGS treatments (eight with different plant species and one with no plants).

Table 1. Botanical information of the eight selected plant species for VGS experimentation.

| Species name | Common name | Family | Plant type |
|---|---|---|---|
| *Codiaeum variegatum* | Variegated croton | Euphorbiaceae | Shrub |
| *Coleus blumei* | Coleus | Lamiaceae | Herb |
| *Duranta repens* | Golden dewdrop | Verbenaceae | Shrub |
| *Ficus elastica* | Rubber fig | Moraceae | Shrub |
| *Peperomia claviformis* | Peperomia | Piperaceae | Herb |
| *Rhoeo discolor* | Moses-in-the-cradle | Commelinaceae | Herb |
| *Sansevieria trifasciata* | Snake plant | Asparagaceae | Herb |
| *Schefflera octophylla* | Ivy tree | Araliaceae | Shrub |

### 2.3 Plant traits

Plant traits of the eight plant species, such as height, leaf number, leaf area, coverage, leaf angle, LAI and vertical LAI were evaluated at the beginning and end of the experiment. Plant height was measured from the substrate level to the apex. The number of healthy and mature leaves of an average plant was counted for each replicate. Leaf area was determined by taking a digital photograph of a mature and healthy leaf from each replicate (placed on a white board with a scale bar) and processing the images with ImageJ (Version 1.46, National Institutes of Health, USA). Green cover was measured by photographic analysis with ImageJ. The leaf angle was the angle formed between the modular system of the wall and the modular system of the leaf. This angle was 0° when a leaf was pointing vertically upwards or downwards, 90° when it grew horizontally (simplified from Li [22] without considering the daily dynamics of solar angle). Thirty mature and healthy leaves were measured by a protractor with a heavy object hanging freely downwards to set the horizontal level. LAI was computed as (number of leaves × average leaf size)/area of VGS. Vertical LAI was measured for the vertically projected leaf area on the wall surface, and was calculated as LAI × cos (leaf angle).

## 2.4 Temperature and soil moisture measurement

The canopy air temperatures of the VGSs with plants and air temperatures of the VGSs without plants were determined, with the ambient air temperature of an on-site automatic weather station serving as the system control. The cooling capacities of the VGSs were evaluated by comparing the temperatures of VGSs with plants with the temperatures of the VGS without plants. The difference between the air temperature of the bare VGS treatments and the ambient air temperature reflected the evaporative cooling by the substrate and the thermal insulation of the VGSs. Temperature sensors (DS18B20 1-Wire Digital Thermometer, Dallas Semiconductor, USA) were installed in the canopy and the substrate of the treatments to record time-series data of the foliage temperature and substrate temperature. The canopy air temperatures of the VGSs with plants and air temperatures of the VGSs without plants were monitored in the central pot of each module to minimize the possible interference of other treatments.

The substrate moisture content in the pots in all VGS treatments was determined by ECH2O-EC5 moisture sensors (Decagon Devices, Inc, USA) inserted 8 cm into the substrate. The sensors were connected to a signal convertor (Ethernet 1-Wire Host Adapters, Embedded Data Systems, USA) and the data were automatically logged in a computer every 30 min. Air temperatures, substrate moisture and substrate temperatures were averaged half hourly with three replicates. The peak temperature on each day was selected to represent the daily maximum temperature. The temperatures of the eight plant species were compared under various weather (sunny, cloudy and rainy) conditions. The substrate moisture was averaged over 12.00–16.00 h for the analysis of the relationship between substrate moisture and other parameters, during which solar heating on the west-facing wall was most intense and the interference of daily irrigation could be avoided. To minimize possible disturbance of background weather conditions, the correlations were conducted separately for sunny, cloudy and rainy days.

## 2.5 Water balance

The water inputs of VGSs are rainfall (RF) and irrigation (IG), while the water outputs are evapotranspiration (ET) and drainage (DN). The VGS water balance can be expressed as:

$$\Delta \mathrm{W} = (\mathrm{RF} + \mathrm{IG}) - (\mathrm{ET} + \mathrm{DN}) \qquad (1)$$

where $\Delta W$ is the change in substrate water storage. On successive sunny or cloudy days when RF is negligible, Eq. (1) can be simplified as:

$$\Delta W = IG - (ET + DN) \qquad (2)$$

The daily water consumption of the vegetated VGSs was composed of IG plus $\Delta W$. The substrate moisture at 00.00 h was defined as the initial value, which was used to calculate the daily substrate moisture change. Positive values of the daily substrate water storage denote water gain, and vice versa. The daily ET is the depletion of water from vegetation and substrate, which was estimated based on Eq. (2) by subtracting $\Delta W$ from IG.

$$ET = (IG - DN) - \Delta W \qquad (3)$$

$$\Delta W = \Delta W_s \times V_s \div S_v \qquad (4)$$

where $\Delta W_s$ represents the daily substrate change. As the pots only covered part of the total area of the VGSs, the thickness of substrate for the total VGSs was calculated as the substrate volume ($V_s$) divided by the area of the VGSs ($S_v$). The diameter and height of the cylindrical plastic pots were both 10 cm.

## 2.6 Steady-state cooling load

To quantify the potential cooling effect of cooled make-up air extracted by the VGSs installed in the building walls, the steady-state cooling loads of a hypothetical room with and without VGSs were calculated (see below). The size of the air-conditioning system was chosen as that of basic installations in modern buildings in Hong Kong. Based on the Chartered Institute of Building Services Engineers (CIBSE) Guide A [23], the steady-state cooling load was calculated through a steady-state heat balance defined by Eq. (5):

$$Q_{cool} = Q_{internal} + Q_{solar} + Q_{fabric} \qquad (5)$$

where $Q_{cool}$ is the overall cooling load of the air-conditioning system (in watts); $Q_{internal}$ represents heat gains from internal sources, such as people and electrical appliances (in watts); $Q_{solar}$ gives solar energy obtained through glazing (e.g., windows) (in watts); and $Q_{fabric}$ defines heat passing through opaque exterior building envelopes, including both external walls and roofs, through heat conduction (in watts).

As internal gains occur entirely indoors, $Q_{internal}$ can be regarded as identical for both rooms. In addition, vertical greenery is generally arranged such that it does not cover the glazing systems, so its effect on solar gains should be small. Therefore, $Q_{solar}$ can also be regarded as identical for both rooms. This leaves $Q_{fabric}$ as the main parameter that differs among different experimental conditions, due to potential temperature differences caused by various plant species.

To quantify the energy saving of VGSs with different plant species, a hypothetical room was proposed. According to the Hong Kong Housing Authority [24], the average living space per person and the average household size are 13.1 $m^2$ and 2.9 persons, respectively, thus the average apartment size in Hong Kong is approximately 38.0 $m^2$. Hence, the hypothetical room had dimensions of 6 m (L) × 6 m (W) × 3 m (H), with a gross floor area of 36 $m^2$. The heat transfer through one external wall was calculated using Eq. (6):

$$Q_{facade} = U \cdot A \cdot \Delta T = U \cdot A \cdot (T_{out} - T_{in}) \qquad (6)$$

where U is the heat transfer coefficient, in $W/m^2$ °C; A is the surface area of each wall, in $m^2$; while $\Delta T$ is the difference between $T_{in}$ and $T_{out}$, in °C.

Based on the CIBSE Guide A [23], the indoor temperature, $T_{in}$, was set as 25°C, and used as the indoor design temperature for summer applications. For buildings without vertical greenery, $T_{out}$ was defined according to the measured temperatures at the onsite weather station, using a 99% confidence interval, which means that for 99% of the time during the measurement period the temperature should be below this level. For buildings installed with VGSs, $T_{out}$ was defined as the canopy air temperature of the vegetated VGSs, on the west façade of the testing rooms, again calculated using the criterion of a 99% confidence interval. As suggested by the UK regulations Part L1A [25], the U-value was set as 0.35 $W/m^2$ °C for external walls. When comparing the cooling effect of the vegetated VGSs, the temperature data from the weather station were used for the bare VGSs, while the mean canopy air temperatures were used for the vegetated VGSs. In addition, heat gain for each plant species on the westerly wall of the hypothetical room was calculated and compared, to determine the best plant species for VGSs in terms of thermal performance.

## 3 Results and discussion

### 3.1 Plant traits

The traits of the eight plant species at the beginning of the experiment are shown in Figure 2. *F. elastica* had the largest values of height, cover and leaf area. The leaf number of *D. repens* was significantly greater than those of *P. claviformis*, *S. trifasciata*, *C. variegatum* and *F. elastica*. The LAI of *P. claviformis* and *S. trifasciata* was significantly greater than those of *C. blumei*, *C. variegatum* and *D. repens*. The vertical LAI of *P. claviformis* was significantly greater than those of the other plants, with a value of 1.27, while the LAI of *C. variegatum* was the lowest at 0.42.

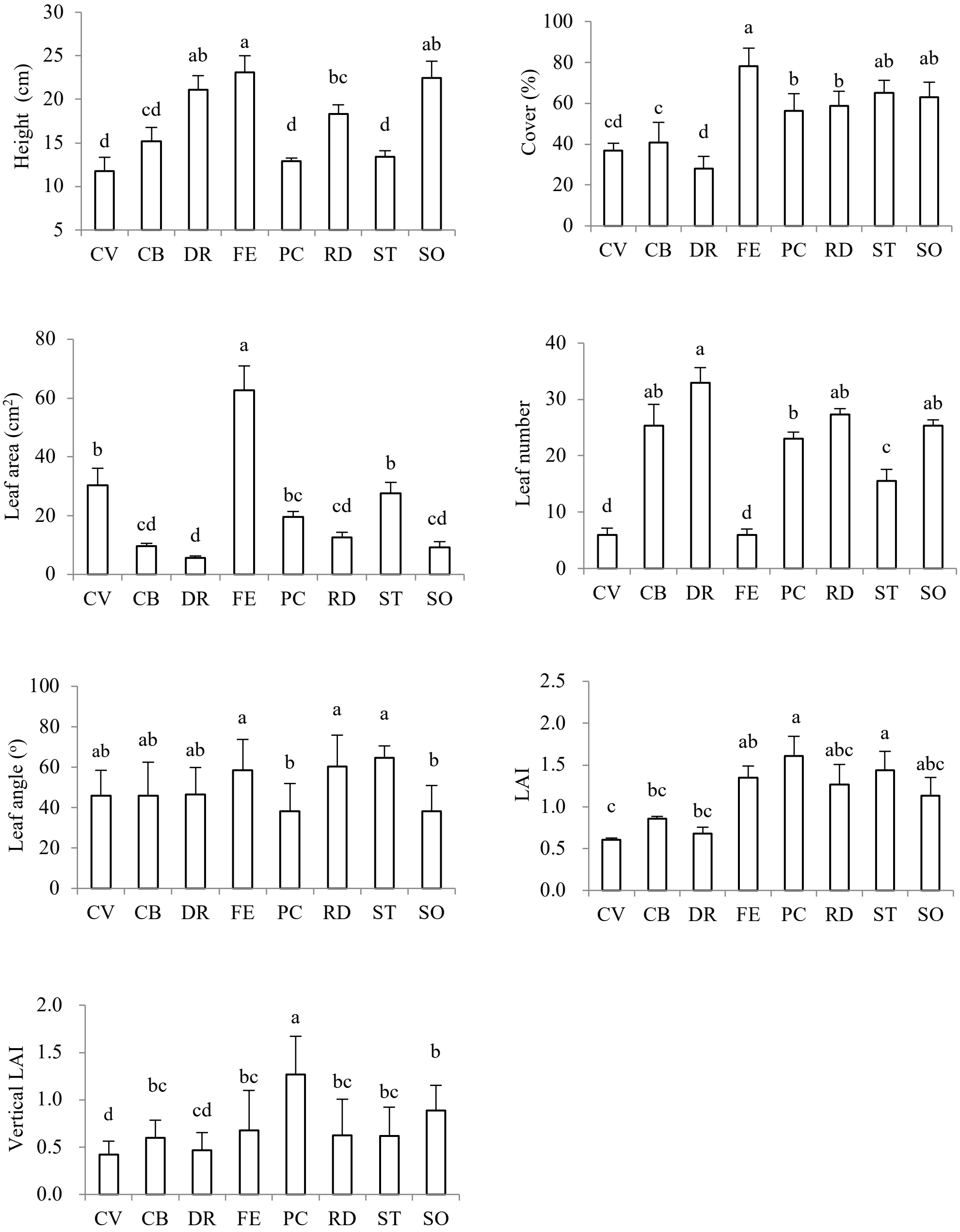


Figure 2. Height, cover, leaf area, leaf number, leaf angle, LAI and vertical LAI of the eight plant species at the beginning of the experiment. Differences between plant

species were statistically analyzed by one-way ANOVA followed by Tukey's HSD post-hoc test (different letters denote significant differences among the eight plants at $p < 0.05$). Abbreviations for plant species: *Codiaeum variegatum* (CV); *Coleus blumei* (CB); *Duranta repens* (DR); *Ficus elastica* (FE); *Peperomia claviformis* (PC); *Rhoeo discolor* (RD); *Sansevieria trifasciata* (ST); *Schefflera octophylla* (SO).

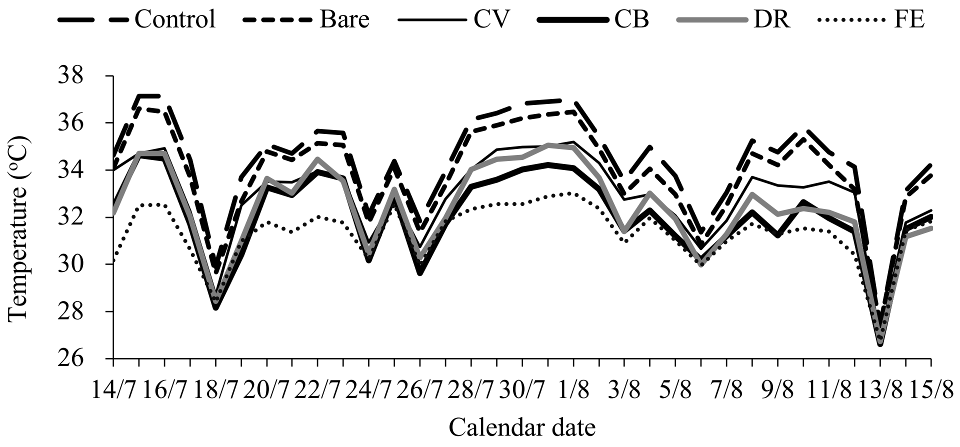
The eight species differed considerably in terms of plant cover, with *F. elastica* having the highest initial cover, of 78.1%. *P. claviformis* had the highest LAI and vertical LAI. The poor growth performance of *C. variegatum* and *D. repens* could be explained by the outdoor environmental conditions, specifically the high temperature and strong solar radiation in summer. The shallow substrate in the VGSs also partially accounted for the restricted growth and reproduction of these two species. Species with low canopy growth parameters, such as *C. variegatum* and *D. repens*, are believed to be both esthetically and ecologically poorer in urban environments, and thus the other plant species studied would be more suitable to VGSs in outdoor environments subject to a low nutrient supply, possible water stress, high temperature and strong solar radiation.

Compared with green façades planted with climber plants, living walls have wider plant diversity, such as creepers, grasses, herbs, ferns and even small shrubs. In this study, differences were noted between herbs and shrubs with respect to plant cover and LAI, in that the four herbs tended to be shorter and have greater leaf number. Despite the thin (10 cm) substrate used in the VGS modules, both the herbs and shrubs with higher water and heat tolerance displayed good growth performance in the outdoor building envelope. The heat stress in summer creates an exposed and harsh environment for vegetation in Hong Kong [4,26]. Nonetheless, plants with good growth performance can achieve full cover and provide significant ecological benefits [18], making them key to successful establishment of VGSs. Hence, the use of plants with a robust capacity to withstand high outdoor temperature and water stress is essential to realize the multiple ecological benefits of VGSs for building envelopes and microclimates [26,27].

## 3.2 Temperature reduction

### 3.2.1 Canopy air temperature dynamics

The canopy air temperatures of the eight plant species in the VGSs were compared with the ambient air temperature of the weather station (Figure 3). The experimental period (14 July to 15 August 2014) was hot and sunny under the prolonged dominance of the subtropical ridge (Figure A1). The daily maximum air temperatures of the weather station and the bare VGSs were consistently higher than the canopy-air temperature of the vegetated VGSs. The temperature peaks and troughs of the VGSs with and without plant species were synchronous with the control, but the amplitude of fluctuation of the control exceeded those of the VGSs. The daily maximum temperatures of the control were higher, with 39.4% (13 out of 33) being >35°C, while in the bare VGSs, only 33.3% (11 out of 33) were >35°C. The daily maximum temperatures of the VGSs never exceeded that of the control. *F. elastica* had the best thermal performance in terms of daily maximum temperature reduction, ranging from 0.6°C (August 13th) to 4.6°C (July 15th). In contrast, the temperature reduction performance of *C. variegatum* was the lowest, with reductions ranging from 0.6°C (August 13th) to 2.4°C (July 15th).



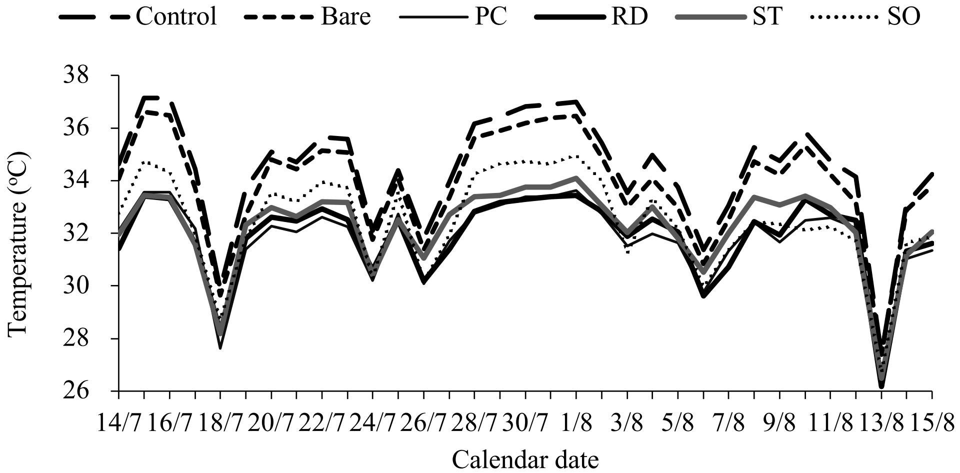


Figure 3. Canopy temperature changes of VGSs with the four herb and four shrub species, bare VGS and the control. Abbreviations for plant species: *Codiaeum variegatum* (CV); *Coleus blumei* (CB); *Duranta repens* (DR); *Ficus elastica* (FE); *Peperomia claviformis* (PC); *Rhoeo discolor* (RD); *Sansevieria trifasciata* (ST); *Schefflera octophylla* (SO).

The use of VGSs resulted in considerable differences in the daily maximum temperature between the canopy air and the ambient air under three typical summer weather conditions (from July to August). *F. elastica* showed the greatest ability for vegetative cooling of the daily maximum canopy-air temperature on sunny days, with a reduction of 3.8°C, which was significantly higher than the other species (Figure 4). The reduction of daily maximum canopy-air temperature by these eight species showed similar patterns on cloudy and rainy days as on sunny days. The temperature reductions achieved on sunny days were 1.8–3.8°C, while the corresponding ranges on cloudy and rainy days were 1.2–2.5 and 1.2–2.4°C, respectively.

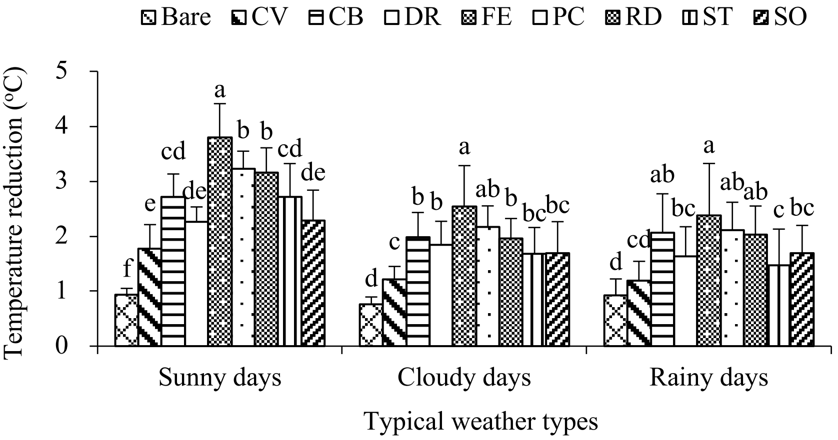


Figure 4. Daily maximum temperature reduction abilities of the nine treatments under different weather conditions. Differences between the means of the different temperature reduction abilities of the nine treatments were statistically analyzed by one-way ANOVA followed by Tukey's HSD post-hoc test (different letters denote significant differences among the nine treatments at $p < 0.05$). Abbreviations for plant species: *Codiaeum variegatum* (CV); *Coleus blumei* (CB); *Duranta repens* (DR); *Ficus elastica* (FE); *Peperomia claviformis* (PC); *Rhoeo discolor* (RD); *Sansevieria trifasciata* (ST); *Schefflera octophylla* (SO).

Substantial diurnal variations were found in the thermal performance of the VGSs. The notable reduction in the daily maximum air temperature is attributed to passive shading and insulation in tandem with active ET [9]. The temperature reduction by the plant canopies of 13 climbing plant species was previously found to be 2.2–2.7°C on sunny days and 1.5–1.8°C on cloudy days in Hong Kong [26], which was slightly lower than the canopy temperature reduction of the VGSs in this study, which may be attributable to the thinner canopies of the climbers. The temperature reduction of the vegetated VGSs was significantly greater than that of the bare VGSs on cloudy and rainy days in this study, which is largely attributable to the solar radiation interception by vegetation [28].

### 3.2.2 Substrate temperature dynamics and water balance of eight plant species

The daily water balance showed remarkable variation between VGSs (Table 2). The VGSs experienced water depletion on sunny and cloudy days, during which *C. blumei* and *D. repens* registered the largest water storage changes. The water reserve in VGSs keeps the substrate moist and provides a water supply in daytime. Hence, water storage plays a significant role under high solar radiation and air temperature, especially at midday in summer. On sunny and cloudy days, *F. elastica* and *C. blumei* consumed the most water, due to the stronger ET effect. Therefore, the daily ET is a key factor that determines the water consumption of VGSs.

Table 2. Diurnal water balance of the VGSs with eight plant species on a sunny day (July 15th) and a cloudy day (July 21st).

| | | ΔWater consumption (Irrigation - drainage) (mm) | Moisture ($m^3$ $m^{-3}$) | | Substrate storage change (mm) | Daily ET (mm) |
|---|---|---|---|---|---|---|
| | | | Daily initial | Daily change | | |
| Sunny days | Bare | 3.4 | 0.347 | -0.029 | -0.8 | 4.2 |
| | CV | 2.0 | 0.322 | -0.025 | -0.7 | 2.7 |
| | CB | 2.1 | 0.320 | -0.040 | -1.1 | 4.1 |
| | DR | 1.8 | 0.325 | -0.044 | -1.2 | 3.7 |
| | FE | 3.6 | 0.306 | -0.026 | -0.7 | 4.3 |
| | PC | 1.8 | 0.342 | -0.036 | -1.0 | 3.4 |
| | RD | 2.6 | 0.324 | -0.025 | -0.7 | 3.3 |
| | ST | 1.6 | 0.347 | -0.018 | -0.5 | 2.1 |
| | SO | 2.5 | 0.314 | -0.028 | -0.8 | 3.1 |
| Cloudy days | Bare | 1.0 | 0.359 | -0.013 | -0.4 | 1.3 |
| | CV | 2.1 | 0.332 | -0.016 | -0.5 | 2.6 |
| | CB | 1.7 | 0.330 | -0.032 | -0.9 | 3.6 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| DR | 1.4 | 0.334 | -0.035 | -1.0 | 3.3 |
| FE | 3.4 | 0.315 | -0.025 | -0.7 | 4.1 |
| PC | 1.8 | 0.363 | -0.026 | -0.7 | 2.6 |
| RD | 2.5 | 0.318 | -0.024 | -0.7 | 3.2 |
| ST | 0.7 | 0.350 | -0.011 | -0.3 | 1.0 |
| SO | 2.5 | 0.323 | -0.015 | -0.4 | 2.9 |

Abbreviations for plant species: *Codiaeum variegatum* (CV); *Coleus blumei* (CB); *Duranta repens* (DR); *Ficus elastica* (FE); *Peperomia claviformis* (PC); *Rhoeo discolor* (RD); *Sansevieria trifasciata* (ST); *Schefflera octophylla* (SO).

For the initial substrate moisture at 00.00 h, which depends on irrigation and drainage, the lowest value for any VGS was 0.306 $m^3$ $m^{-3}$ (Table 2). This indicated that the eight species had the ability to resist the effects of outdoor heat stress and sustain substrate moisture. Nonetheless, the moisture contents of the vegetated VGSs (0.314 to 0.363 $m^3$ $m^{-3}$) were lower than the saturated moisture of 0.422 $m^3$ $m^{-3}$. This shows that the negative effects of prolonged insufficient watering during the long hot days of summer should not be overlooked.

On the sunny day (July 15th) the high direct sun exposure caused much water loss from the substrate through evaporation. For the bare treatment, the substrate in small pots was rapidly evaporated and the substrate moisture decreased. For the eight treatments with plant species, the shading effect of vegetation alleviated the evaporation from the substrate. Meanwhile, the plants also brought about some water loss through transpiration, but their transpiration rates varied. Overall, on sunny days, the daily ET of the bare treatment was higher than those of VGSs with plants.

On the cloudy day (July 21st), water loss of the bare treatment was through substrate evaporation, but for the eight treatments with plants, apart from the evaporation of substrate, plant transpiration also brought about much water loss in the substrate. When compared with most vegetated VGSs, the bare VGS treatment had less water loss on that day.

In green roofs, ET is largely dependent on solar radiation, relative humidity and wind speed [20]. Consistently, the difference between daily ET on sunny and cloudy days indicated that the daily ET of VGSs was regulated by the weather conditions.

The mean daily maximum substrate temperature range of the vegetated VGSs was 27.2–28.4°C (Table 3). This small difference indicated that the substrate temperature was relatively unaffected by plant species when the substrate moisture range was 0.280–0.363 $m^3$ $m^{-3}$ (Table 2 and 3).

Table 3. Daily maximum substrate temperature of the VGSs with eight plant species from July 14th to August 15th (33 days).

| | | Daily maximum temperature range (°C) | Mean daily maximum temperature (°C) | Mean daily maximum temperature reduction (°C) | | |
|---|---|---|---|---|---|---|
| | | | | Sunny days | Cloudy days | Rainy days |
| Air temperature | Control | 26.5–37.2 | 29.4 | | | |
| Substrate temperature | Bare | 26.3–30.9 | 27.3 | 2.8 | 1.4 | -0.2 |
| | CV | 26.4–32.6 | 28.4 | 3.0 | 1.5 | -0.4 |
| | CB | 26.6–32.0 | 28.1 | 3.1 | 1.4 | -0.6 |
| | DR | 26.3–32.4 | 28.5 | 2.9 | 1.4 | -0.6 |
| | FE | 26.6–31.2 | 27.9 | 2.8 | 1.3 | -0.5 |
| | PC | 26.7–30.3 | 27.2 | 3.2 | 1.6 | -0.7 |
| | RD | 26.7–30.8 | 27.8 | 3.0 | 1.6 | -0.4 |
| | ST | 26.6–30.7 | 27.2 | 3.4 | 1.7 | -0.9 |
| | SO | 26.6–31.7 | 28.2 | 2.7 | 1.3 | -0.4 |

Cheng et al. [9] suggested that in Hong Kong, in terms of substrate temperature reduction, substrates were cooler than the ambient air by an average of 1°C. The difference between substrates and ambient temperatures obtained in this study was slightly greater. On sunny and cloudy days, the daily maximum substrate temperatures of the VGSs were lower than the control, while on rainy days they were higher than the control. The daily maximum substrate temperature of the bare VGSs on sunny and cloudy days was 2.8°C and 1.4°C, respectively, while those for vegetated VGSs were 2.7–3.4°C and 1.3–1.7°C, respectively. On rainy days, the mean daily maximum substrate temperature reduction of the bare VGSs was -0.2°C, while the values for the vegetated VGSs were 0.4–0.9°C: this suggests that on rainy days the vegetation in VGSs may block wind and rain and increase thermal capacity, thereby warming the substrate.

### 3.2.3 Correlation between plant traits, substrate moisture and temperatures

Pearson correlation analysis was performed for the plant traits, moisture and both temperatures, i.e., that of the substrate surface and that behind the canopy created by the plant species (Table 4). The canopy temperature reduction ability of these species increased with canopy cover and LAI. The other parameters measured, namely height, leaf area, leaf number, vertical LAI, daily ET and substrate moisture, were not significant with respect to canopy temperature. There was, however, a significant correlation ($p < 0.05$) between substrate moisture and the daily maximum substrate temperature on sunny and rainy days.

In terms of correlations between plant traits and moisture, the substrate moisture decreased with the daily ET on sunny days. No significant correlations were found between daily ET and other plant traits. Furthermore, as shown in the Appendix, a one-way ANOVA showed that only the substrate temperature varied significantly among the VGSs with four herbs and four shrubs on sunny days, while there were no significant variations between these herbs and shrubs in terms of plant traits or canopy temperatures. This indicated that the different behaviors of the different species can be attributed to their traits like canopy cover and LAI, instead of plant functional type.

Table 4. Pearson correlation between canopy and substrate temperature and traits of the canopy and substrate of the eight plant species.

| | Daily ET | | Canopy temperature | | | Substrate temperature | | |
|---|---|---|---|---|---|---|---|---|
| | Sunny days | Cloudy days | Sunny days | Cloudy days | Rainy days | Sunny days | Cloudy days | Rainy days |
| Leaf area (cm$^2$) | 0.481 | 0.406 | -0.518 | -0.371 | -0.311 | 0.076 | 0.493 | 0.007 |
| Leaf number | -0.167 | -0.174 | 0.113 | -0.078 | -0.078 | 0.050 | -0.603 | 0.055 |
| Canopy cover (%) | 0.358 | 0.294 | -0.707* | -0.547 | -0.513 | 0.051 | 0.475 | 0.073 |
| LAI | 0.135 | 0.206 | -0.751* | -0.630 | -0.556 | -0.361 | -0.061 | 0.422 |
| Vertical LAI | 0.044 | 0.098 | -0.413 | -0.461 | -0.450 | -0.100 | -0.027 | 0.198 |
| Height | 0.702 | 0.591 | -0.305 | -0.433 | -0.400 | -0.629 | 0.210 | -0.408 |
| Daily ET (mm): sunny day | \ | \ | -0.606 | \ | \ | 0.692 | \ | \ |
| Daily ET (mm): cloudy day | \ | \ | \ | -0.531 | \ | \ | 0.360 | \ |
| Substrate moisture (m$^3$ m$^{-3}$): sunny days | -0.844* | \ | 0.123 | \ | \ | -0.871* | \ | \ |
| Substrate moisture (m$^3$ m$^{-3}$): cloudy days | \ | -0.690 | \ | 0.199 | \ | \ | -0.424 | \ |
| Substrate moisture (m$^3$ m$^{-3}$): rainy days | \ | \ | \ | \ | 0.330 | \ | \ | 0.812* |

[*] denotes significant correlations at $p < 0.05$.

Although substrate moisture is often considered indicative of the insulating capacity of VGSs, the correlations between substrate moisture, ET and canopy temperature reduction were non-significant in this study (Table 4). The lack of influence of substrate moisture and plant parameters on ET might be explained by the following factors: (1) the water storage in the water retention zone and the design of the VGS panel affecting the accuracy of the data of water uptake and daily ET; (2) extensive variation among the eight plant species in leaf stomatal size and density and photosynthetic pathway (plant transpiration rate and midday depression of photosynthesis, etc.) leading to profound and complex effects on the ET cooling via plant transpiration (e.g., *S. trifasciata* is a crassulacean acid metabolism (CAM) plant species that has a photosynthetic carbon-assimilation pathway with high water-use efficiency [29]); (3) limited water-holding capacity of the 10-cm-thin substrate in the VGSs, which confined the ET extraction rate in the substrate at the experimental site. Similarly, the fact that the ET was affected by the above factors asynchronously may explain why ET did not significantly enhance canopy cooling of the VGSs.

Canopy temperature reduction will undoubtedly be influenced by canopy traits. The plant canopy of the various species served as a buffer against temperature fluctuations under the canopy and the underlying wall surface. Our results suggested that canopy temperature reduction increased with LAI and canopy cover, which were consistent with previous studies [13,17]. However, the present study did not show a significant correlation between leaf area and canopy air temperature, despite the suggestion by Charoenkit and Yiemwattana [7] that plants with high LAI and small leaves were the most effective at creating a cool plant surface. The discrepancy may be attributable to the smaller number of plant species (only three) in the study of Charoenkit and Yiemwattana, compared with the eight species used in this study.

On sunny days, daily ET had no determining effect on foliar thermal properties; rather, the shading effect of plants played a major role in regulating canopy temperature via the thermal properties of the LAI and the cover of the vegetation. This indicated that the evaporative cooling of the substrate was less effective in canopy temperature reduction. Therefore, the most effective strategy for maximizing the benefits of VGSs is to increase the plant cover and LAI, but not the ET cooling of the substrate. This study may provide guidance for enhancing the design and management of VGSs with reference to water and thermal behavior.

Substrate moisture affected the thermal mass of the VGSs and the ecophysiological processes of the vegetation. The substrate cooling effect (expressed as the temperature difference between ambient air and substrate) was strongly regulated by the substrate moisture, which was consistent with a previous study [9]. On sunny days, high substrate moisture was correlated with lower substrate temperature. The heating of substrate moisture by solar radiation reduced substrate temperature on sunny days. On rainy days, high substrate moisture played the opposite role, elevating substrate temperature by raising the thermal capacity. Thus, the substrate moisture of VGSs could notably cool the substrate on sunny days, and warm the substrate on rainy days, which were consistent with the findings by Jim and Peng [20] about green roofs. Given that the limited data replication and the small size of VGSs in this study may have affected the ET, substrate moisture and thermal properties of the VGSs, further study is needed to clarify the ecophysiological processes of VGSs in temperature reduction and thermal regulation.

### 3.3 Steady-state heat conduction

Heat conduction of the hypothetical rooms with and without VGSs during the one-year period was calculated based on the air temperature of the vegetated VGSs and at the weather station (control) (Table 5). For the eight plant species, air temperature refers to the canopy temperature of VGSs with different species.

Table 5. Heat conduction of hypothetical rooms with and without VGSs.

| | Air temperature (°C) | Heat conduction (W) | Heat conduction reduction (W) | Heat conduction reduction (%) | Heat conduction reduction per unit area by VGS (W $m^{-2}$) |
|---|---|---|---|---|---|
| Control | 40.1 | 95.3 | | | |
| CV | 37.3 | 77.5 | 17.8 | 18.7% | 0.99 |
| CB | 35.8 | 68.0 | 27.2 | 28.6% | 1.51 |
| DR | 36.5 | 72.5 | 22.8 | 23.9% | 1.27 |
| FE | 34.1 | 57.3 | 37.9 | 39.8% | 2.11 |
| PC | 34.6 | 60.5 | 34.8 | 36.5% | 1.93 |
| RD | 34.9 | 62.4 | 32.9 | 34.5% | 1.83 |
| ST | 35.6 | 66.8 | 28.5 | 29.9% | 1.58 |
| SO | 36.7 | 73.7 | 21.5 | 22.6% | 1.20 |
| Average | 35.7 | 67.3 | 27.9 | 29.3% | 1.55 |

The VGS canopy also acts as a ventilation blind, in which warm air is dissipated from the top and replaced by cool air from the exterior [30]. VGSs can thus reduce unwanted heat flows from outdoors to indoors, and serve as surrogate green spaces in building environments [31-34]. The application of VGSs with commonly used plant species on building envelopes can reduce steady-state heat conduction. In this study, the vegetated VGSs reduced heat conduction by 18.7% to 39.8%. This was greater than the cooling-load reduction of 16% in summer achieved in an empirical study of VGSs on a southwest-facing wall in Hong Kong [1]. The discrepancy may be due to the varied plant characteristics of the different plant species used.

With the widespread application of VGSs all over the world, especially in high-density cities, most of the installations have met building specifications regarding safety and wall loading, which are technically proven and reliable. VGS is a good solution for energy saving and thermal comfort for both high-rise and low-rise buildings in densely packed cities. Compared with the application on tower blocks, VGSs on low-rise flats are easier to install and maintain at lower costs.

With regard to the canopy temperatures of the vegetated VGSs, *F. elastica* and *P. claviformis* gave the greatest reductions in cooling load. *F. elastica* gave the best performance in daily maximum temperature-reduction due to its high LAI and cover (Figures 3 and 4, Table 5). During periods of high temperature, canopies with higher cover and LAI enable VGSs to absorb more energy, and transfer less heat to the ambient environment via heat stress. In contrast, *C. variegatum* and *D. repens*, with lower foliage density due to their lower canopy cover and LAI, were more efficient in heat transfer and thermal conduction.

The vegetated VGSs thus varied significantly with respect to steady-state heat transfer, showing that it is imperative to carefully select plants with regard to their specific ecological functions to ensure their successful use in VGSs. Therefore, due to the effect of plant traits on their thermal properties, species with a high LAI and good canopy cover are most suitable for esthetics and biodiversity, and also for their ecological utility, as these species exhibit the optimal synergistic effects of shading, ET and heat transfer.

The lack of data on building wall temperature in this study may have affected the calculated canopy and substrate temperatures, and thus further study is needed to clarify the interactive mechanisms between building envelopes and VGSs. Experiments with more extensive VGSs on building envelopes may also need to be performed to validate the data used and obtained in this study, with respect to the energy savings associated with VGSs.

## 4 Conclusions

This study provides valuable information on the effects of plant traits and substrate moisture on the thermal performance of VGSs in subtropical Hong Kong. It was found that vegetated VGSs with different plant species varied significantly in their capability for reduction in temperature and heat transfer beneath the plant canopy under different weather conditions in summer. The use of plant species with higher canopy cover and LAI in the VGSs ensured greater reductions in canopy temperature.

The shading effect by vegetation in VGSs was found to be the main contributor to canopy temperature reduction, and an increase in cover enhanced this effect. Plants with higher LAI were more effective in terms of their shading effect and the ET cooling effect of vegetation. The application of VGSs on building envelopes reduced steady-state heat conduction by 18.7–39.8%. Based on the canopy temperatures of the VGSs with different plant species, the reduction in cooling load was greatest for *F. elastica*.

These findings show that judicious plant selection is key to realizing the esthetic and ecological benefits of VGSs, such as reduction of the canopy temperature and the cooling load of air conditioning. VGSs featuring plants with high canopy cover and LAI value (e.g. *F. elastica*) could serve as surrogate green spaces, absorb more heat and reduce unwanted heat flows from outdoors to indoors via heat stress during high temperature periods in building environments.

VGSs with different plant species varied in substrate moisture content due to differences in transpiration of substrate water and evaporation from vegetation. The lack of a significant correlation between substrate moisture, ET and canopy temperature indicated that substrate moisture and ET did not significantly enhance the canopy cooling of the VGSs. Notably, the substrate moisture in VGSs cooled the substrate on sunny days, but warmed the substrate on rainy days. The significant correlation between the substrate moisture and substrate temperature reduction indicated that sufficient substrate water not only regulated plant growth performance and health, but also determined the substrate thermal properties and the water supply for ET.

Thus, the traits and ET capacity of the vegetation and substrate influence the thermal behavior of VGSs. These findings confirm that knowledge of the particular plant species used, their configuration and their growth stage are key factors in designing optimal VGSs for building envelopes.

## Appendix

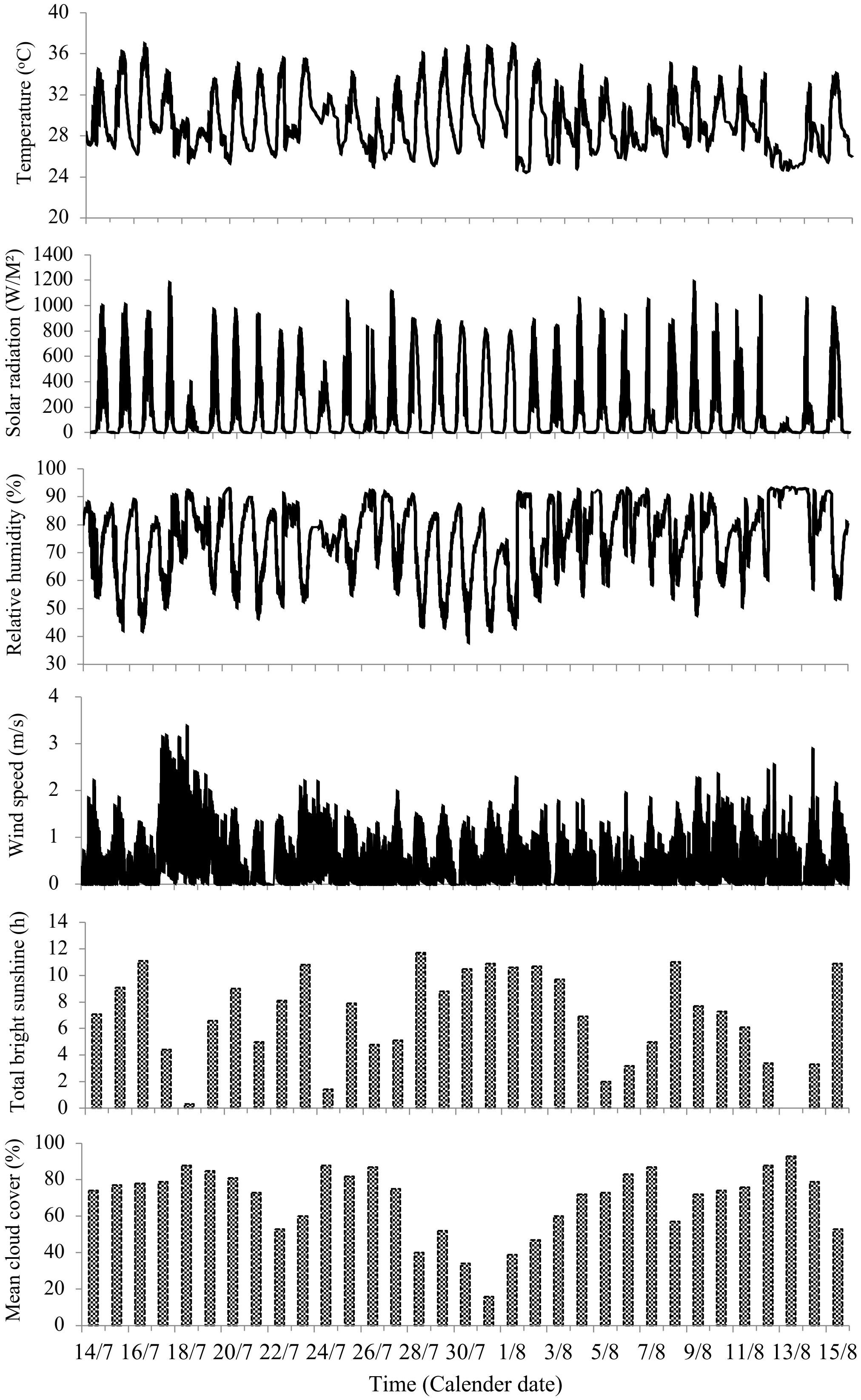


Figure A1. Meteorological conditions from 14 July to 15 August 2014.

Table A1. Comparison between the plant traits, canopy and substrate temperature of four herbs and four shrubs. Differences between plant species were statistically analyzed by one-way ANOVA followed by Tukey's HSD post-hoc test (different letters denote significant differences among the eight plants at $p < 0.05$).

| | Leaf size (cm$^2$) | Leaf number | Canopy coverage (%) | LAI | Vertical LAI | Height (cm) | Daily ET (mm) | | Substrate moisture (m$^3$ m$^{-3}$) | | | Canopy temperature (°C) | | | Substrate temperature (°C) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sunny days | Cloudy days | Sunny days | Cloudy days | Rainy days | Sunny days | Cloudy days | Rainy days | Sunny days | Cloudy days | Rainy days |
| Herbs | 17.3 | 22.8 | 0.6 | 1.3 | 0.8 | 15.0 | 2.9 | 2.3 | 0.3 | 0.3 | 0.3 | 33.0 | 32.1 | 31.3 | 27.7b | 27.9 | 27.9 |
| Shrubs | 27.0 | 17.6 | 0.5 | 0.9 | 0.6 | 19.6 | 3.3 | 3.0 | 0.3 | 0.3 | 0.3 | 33.5 | 32.2 | 31.5 | 28.1a | 28.0 | 27.7 |

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